Leveraging Science and Technology

The Department of Energy and the Department of Defense have historically shared Lawrence Livermore's wealth of national security resources. The results are more science and technology for the investment and better assurance that the nation's security and defense needs will be met.

THE three DOE national security laboratories—Lawrence Livermore, Los Alamos, and Sandia—have a technology base of interest to the Department of Defense. Their nuclear weapons technology can be leveraged to address the DOD nonnuclear security mission. Therefore, it's not surprising that DOE and DOD have a long history of collaboration at the three laboratories. At Lawrence Livermore, that collaboration dates at least as far back as February 1956, when Edward Teller made a bold pledge to deliver to DOD a smaller, lighter warhead for the Polaris missile and do so on an extremely short schedule. Lawrence Livermore scientists took up the challenge and made good on Teller's promise. It was one of many instances where scientists from DOE national security laboratories were to fulfill DOD requests.

Later, during the Cold War, a Navy Trident test missile blew up and extensively damaged the testing range. Lawrence Livermore, working with Los Alamos and two Navy laboratories, unraveled the cause of the explosion, which led to the development of a safer, high-energy propellant to put the Trident missile back on track. More recently, in Kuwait while the Persian Gulf War was being waged, Livermore's Atmospheric Release Advisory Capability tracked smoke plumes from torched oil wells so pilots could plan safe flight paths and environmental air monitors could estimate the plumes' health effects.

During war and in less turbulent times, the Laboratory delivers services and products to DOD. They range from a new missile warhead to a new direct, in-line detonator that provides a safe, reliable electronic fuse used to initiate explosives in munitions. Lawrence Livermore has also provided DOD with items such as the LX-14 explosive, currently found inside DOD's TOW, Hellfire, Javelin, and BAT antiarmor munitions.

A Two-Way Exchange

DOD has long recognized that Livermore—indeed, all the DOE national security laboratories—has unique capabilities that can be leveraged for DOD purposes. Traditionally, DOD has provided additional funding to the national laboratories to extend projects toward conventional weapons applications. In one instance, to maximize this leveraging, the funding arrangement was formalized in 1985 in a Memorandum of Understanding (MOU), which established a joint munitions program between the DOE national laboratories and DOD.

The MOU program at Livermore was managed for many years by chemist Milton Finger, now the Laboratory's Deputy Director for DOD Programs. He subsequently turned that responsibility to Al Holt, and currently Dennis Baum manages the program. Finger says that "the program provides a window through which Lawrence Livermore can be aware of DOD needs and DOD can be knowledgeable of the technologies available at Livermore. DOD can challenge Livermore to contribute innovative science and technology to attack pervasive problems and grand challenges in the defense arena. In addition, Livermore can focus its efforts more efficiently and productively to serve the dual interests of DOE and DOD."

Baum identifies the program's principal technical areas as high explosives, codes, nonnuclear weapons design, fuses, demilitarization, sensors, and advanced materials. Both Finger and Baum point to the program's efficient integration with Laboratory projects and priorities. Consequently, Livermore resources are being used more fully and productively, and DOD derives advantages from Livermore at the same time that Livermore core competencies are enhanced.

The projects described here, which are but a small portion of Livermore's DOD work, demonstrate some of the ways the Laboratory uses technologies for dual national security benefits.

Getting out of Tight Spots

One day, U.S. soldiers under attack in hostile, foreign terrain may find themselves depending on a device developed with the help of Lawrence Livermore. To put an insurmountable obstacle between themselves and the enemy, they pull out a weapon called a

in the National Interest

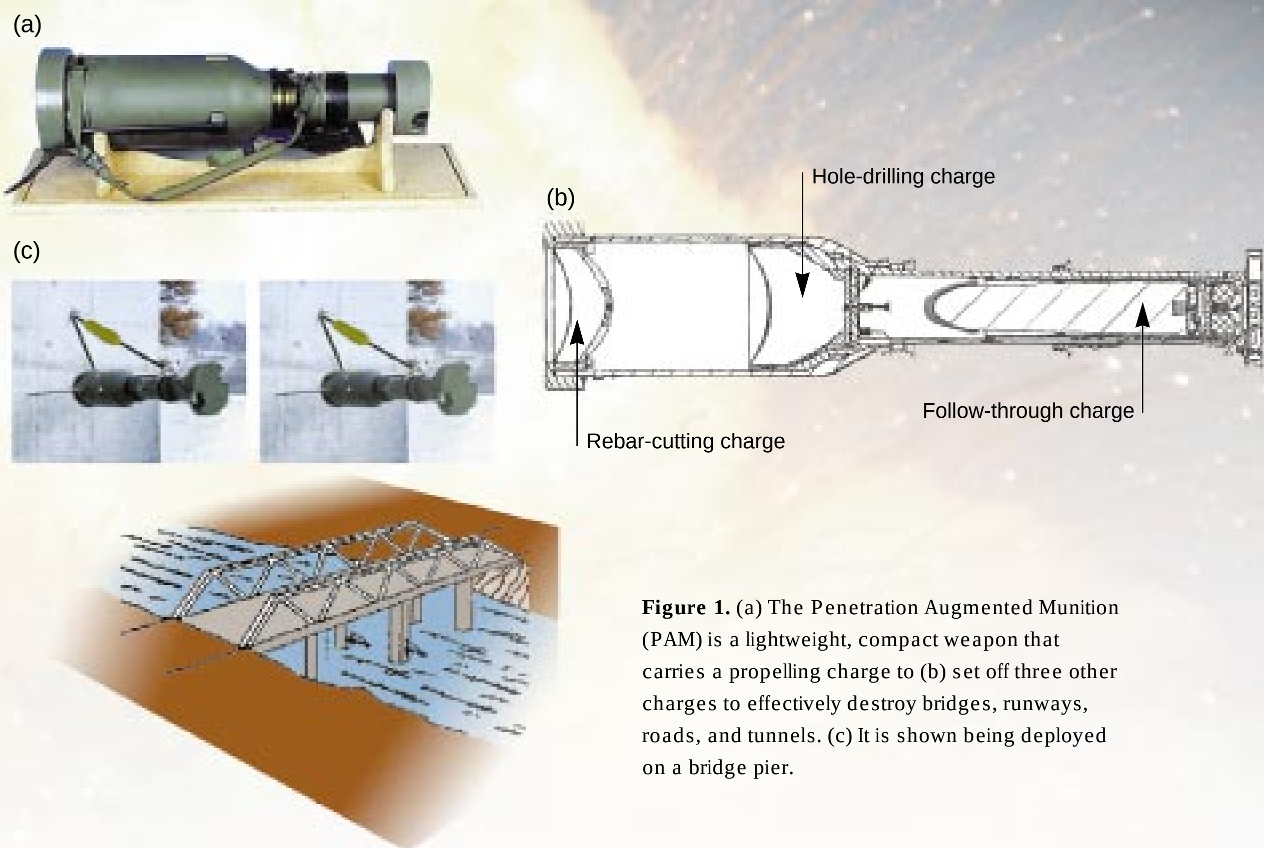

Figure 1. (a) The Penetration Augmented Munition (PAM) is a lightweight, compact weapon that carries a propelling charge to (b) set off three other charges to effectively destroy bridges, runways, roads, and tunnels. (c) It is shown being deployed on a bridge pier.

PAM, or Penetration Augmented Munition. Although compact and lightweight (approximately 35 pounds, 33 inches long), it contains the power of four explosive charges and when deployed, can effectively destroy bridges, runways, roads, and tunnels (Figure 1).

A typical demolition target for the soldiers is a bridge. To destroy it, they must detonate two PAM units simultaneously at the bridge pier. They trigger the PAMs' propelling charges and shoot the warheads directly into the structure. The motion of the propelling charge sets off each PAM's other three charges: one charge cuts through the bridge's concrete rebar, the second makes a deep, narrow hole in the bridge pier, and the third penetrates to the bottom of that hole and detonates. Objective accomplished. The soldiers have hindered enemy mobility.

The genesis of the multistage PAM can be traced to work during the 1980s on a two-stage munition system for the Air Force. Livermore scientists evolved a two-stage munition based on the work of a defense industry contractor into a warhead for a 2,000-pound laser-guided bomb. The Defense Advanced Research Projects Agency sponsored further development of a three-stage munition designed to crater airfield runways. The portable four-stage multicharge PAM—a demolition munition at once compact, light, and effective— was realized under the joint DOD/DOE MOU program.

During the fabrication and testing of the first PAM, the device would not work properly because the shock resulting from the rebar-destroying and hole-drilling charges caused the fuse in in the main penetrating charge to malfunction. Livermore scientists developed a fuse that could survive the explosive shocks and detonate the last charge at the appropriate time.

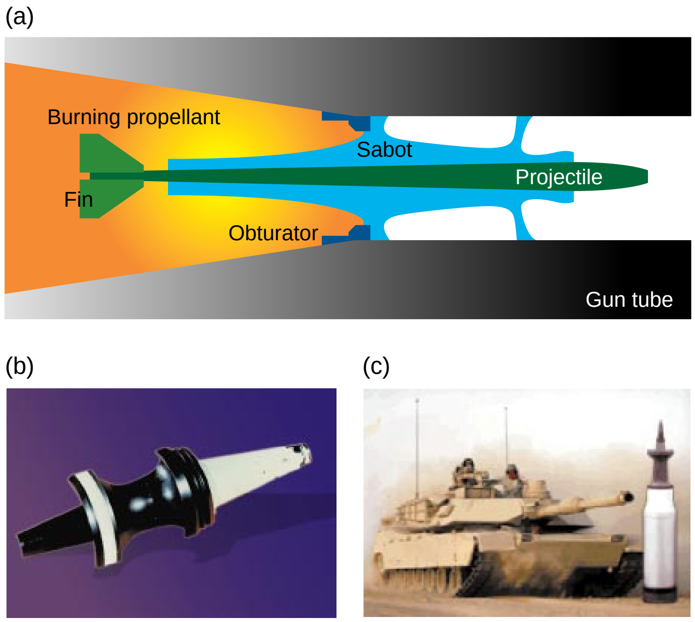

Figure 2. (a) A sabot transfers energy from the weapon propellant to its projectile. (b) Livermore's fiber-composite sabot is (c) part of the Army's weapon of choice for antitank warfare.

Michael J. Murphy, one of the developers of the device, says that the PAM has been designated by the Department of Defense as a "Type Classified Standard for Army Special Operational Forces Use," meaning that DOD has made a firm decision to produce and use it. It is now designated as the XM150. Engineering development, conducted at Alliant Techsystems and under U.S. Army sponsorship with Lawrence Livermore support, is complete.

Strong String and Glue

Engineers in Livermore's Mechanics of Materials Group, led by Steve DeTeresa, were part of a Lawrence Livermore–Army Research Laboratory team that developed a fiber-composite sabot for DOD use. A sabot is a lightweight carrier used both to position a missile or subcaliber projectile inside a gun tube and to transmit energy from the propellant to the projectile (Figure 2). DeTeresa says that the sabot works much like a person throwing a dart, where the thrower's arm movement acts as both the propellant-driving gas and the sabot's energy-gathering pusher (Figure 3).

In general, guns operate with a fixed mass to be propelled out of the gun's tube. The sabot is necessary to transfer propellant energy but is a parasitic weight in terms of projectile target performance. Reducing the sabot's weight allows greater projectile velocity. The weapons thus penetrate deeper, with more lethal results. But materials used to fabricate sabots can only be as lightweight as they are strong enough to withstand great pressures and loads during gun-tube acceleration. Previously, the lightest weight sabots were made of aluminum.

In the past, the search for lighter weight sabot materials focused on metal composites. But researchers were continually frustrated by failure—metal composites simply were too brittle. Attention then shifted toward polymer-based composites, which were being used extensively in thin structures for aerospace applications. Researchers began to consider fiber composites for complex shaped structures that needed to survive multidirectional stresses. Livermore material scientists were asked to help develop a new sabot based on these materials.

DeTeresa relates that some engineers refer whimsically to a fiber composite as "string and glue." It consists of high-strength carbon fibers, which must be laid down and oriented to yield maximal strength and handle maximal stress. Polymer is used to glue together layers of these fibers in a process similar to that used to manufacture plywood. When layers are glued together, the grains of adjacent layers are arranged either at right angles or at some wide angle to each other. Once a piece of the material has been fabricated, it can be machined into the required form. Fairly thick pieces that can withstand high three-dimensional stress are used for sabot material.

Although they have developed an effective, extremely lightweight sabot, development team members continue to investigate which material combinations and fiber architectures will provide ever-greater material strength. They are eager to understand the material's stress responses and failure modes completely, particularly because thin sheets of this material are used for safety-critical components in airplanes.

The team has developed models of fiber-composite materials and is simulating their performance using the Laboratory's DYNA and NIKE structural response codes. One of the models incorporates a misaligned fiber. By analyzing the effects of the imperfect fiber on material properties, the researchers can address how to prevent or minimize those effects. At the same time, they are investigating cheaper ways of producing fiber-composite material.

The Army, the largest consumer of advanced carbon fiber composites in the defense community, is using the fiber-composite sabot in the M829 A2 kinetic energy projectile, the weapon of choice for antitank warfare.

As a result of the sabot work, Livermore holds a patent on the fiber-composite sabot's structure and fabrication process. Livermore and the Army Research Laboratory have won an Army Service Award for developing the sabot. The Livermore engineers are the first non-DOD civilians to receive this award.

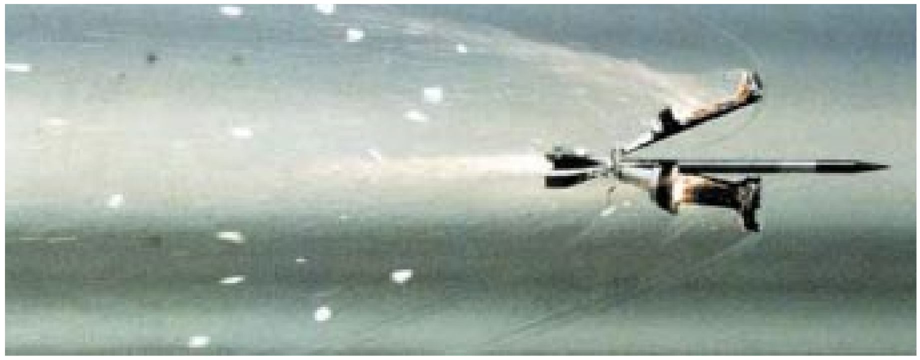

Figure 3. A sabot pushing the weapon projectile toward its target.

Code Optimizes Design

Computational modeling and simulation, already a key component of Livermore problem-solving capability, will become even more dominant as DOE's Accelerated Strategic Computing Initiative continues to increase computational speed and power. Not surprisingly, computer code development is flourishing at Livermore, and many scientists are wearing the dual hats of code developer and code user. Michael J. Murphy, who was involved in the design of the PAM, is one of them. He and Ernest Baker of the U.S. Army Armament Research, Development and Engineering Center have developed a code useful for optimizing warhead designs, including shaped charges (warheads encased in steel or aluminum and consisting of a metal cone, or liner, backed by high explosive). Murphy's code is called GLO (global local optimizer).

GLO directs physics code simulations to optimize the warhead design. It is a powerful tool that saves munitions designers time and produces robust results.

Two key steps are involved in GLO's work. First, it must incorporate a description of an optimum design, based on the kind and degree of damage that designers want the shaped charge to inflict. For example, the goal may be to create a hole of a specified size and depth in a certain target. GLO runs the physics codes and then compares the calculated hole profile with the desired hole profile. Figure 4 shows a simulation of the shaped-charge detonation, jet formation, and subsequent penetration into a target.

The second step optimizes the design using the results of the comparison from the first step. GLO is repeatedly linked to the physics codes and adjusts the shaped-charge design until it obtains as close a match as possible to the specified hole profile. Often, the code that GLO directs is the two-dimensional hydrodynamic code, CALE (C-language arbitrary Lagrangian–Eulerian), in which is embedded a number of parameters defining the overall size and geometry of the shaped charge. For each design considered, GLO specifies the values of the parameters that define the geometries of the shaped-charge explosive and metal cone. CALE calculates the mass and velocity distribution of the jet for each shaped-charge design. GLO's parameters change over the series of calculations to describe different configurations of the shaped charge.

The CALE calculations result in a definition of the geometry of the jet of metal formed when the cone of a particular shaped-charge configuration is compressed by the explosive charge. This definition is used by an analytic penetration code to calculate the jet penetration and the resulting target hole profile.

In a typical overnight optimization run, GLO can evaluate some 250 sets of parameters. The optimum design configuration is selected from these sets. Murphy says that GLO is a "very dedicated assistant working unceasingly to generate numerous iterations of shaped-charge configurations."

From TIGER to CHEETAH

Ron Atkins, head of Livermore's Energetic Materials Center, notes that it's usual for inventors to first try to make their inventions work and then to try to understand how they work. That is certainly the case with high-explosive detonations. Scientists have worked for over a century to understand the physics of detonation properties of explosives long in use. Atkins coordinates a group of projects attempting to expand that understanding further in order to design safer and more powerful explosives as well as to formulate new explosives with properties tailored to specific applications.

One ongoing project is a code that simulates detonations and predicts the results of detonating a specific mixture of chemical reactants. The code is CHEETAH, a fast, scientifically rigorous descendant of Livermore's TIGER and RUBY thermochemical codes. Chemist Laurence Fried and

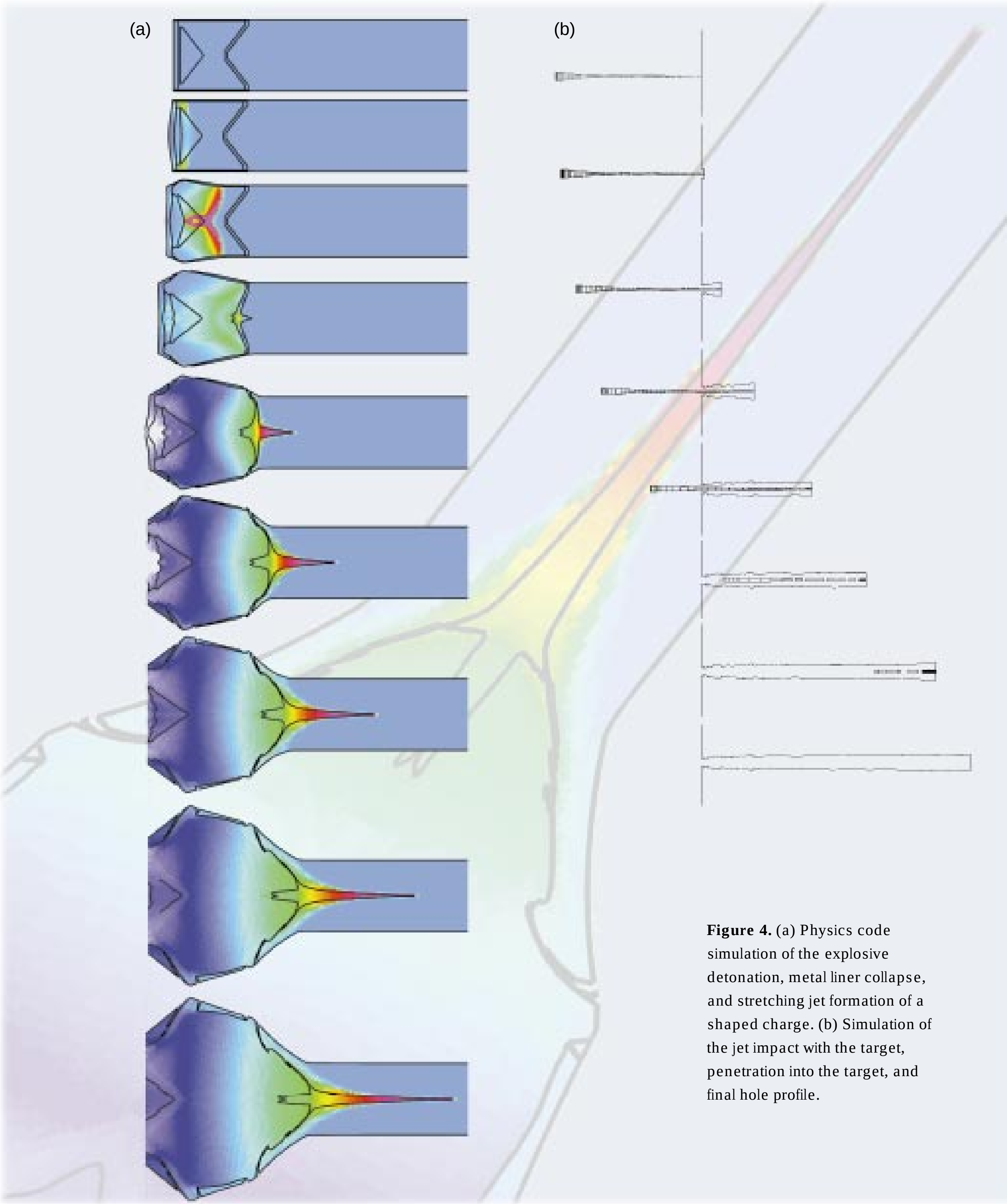

Figure 4. (a) Physics code simulation of the explosive detonation, metal liner collapse, and stretching jet formation of a shaped charge. (b) Simulation of the jet impact with the target, penetration into the target, and final hole profile.

colleagues designed CHEETAH to allow explosives formulators to predict different starting molecules and formulation performance and, hence, to design optimized explosives with specific characteristics.

The newest version of CHEETAH (described in *S&TR*, November 1997, pp. 21–23) is a particularly popular tool for explosives formulators in that it is more user friendly than earlier versions and includes a database of 200 chemical starting reactants and 1,000 possible products. This database saves a user the inconvenience of looking up thermodynamic constants for each chemical. More significantly, the new CHEETAH tracks chemical reactions down to the molecular level to obtain very accurate predictions of the velocity and energy of the detonation.

The earlier version of the code assumed that all reactions occur instantaneously, that all reaction ingredients are consumed completely, and that thermal equilibrium is reached at the same time. In reality, the chemistry of a detonation is much more varied and complicated. Many different molecules are involved, with some reacting more slowly than others, and those slow chemical reactions require a long time to achieve thermochemical equilibrium. Moreover, a variety of chemical reactions takes place during the explosive decomposition of mostly large, energetic-material molecules into small, simple product molecules. The explosive reaction products undergo material changes and occupy different states of pressure, density, and velocity. All these reactions must somehow be represented in the codes to obtain accurate predictions of detonation pressure, velocity, and energy of the detonation.

Fried implemented a kinetic detonation model, based on the Wood–Kirkwood detonation theory, which provides equations of state for complicated mixtures of detonation product molecules. This model accounts for the microscopic mechanical and thermal processes that occur in shock initiation and detonation, and it calculates chemical reaction rates at the molecular level. The calculational results showed CHEETAH effective for modeling many features of slowly reacting explosives.

Fried and his colleagues are continuing to improve CHEETAH by including the effects of high pressure and high temperature on chemical kinetics. They will thus be able to model more complex, slow detonation behavior such as shock initiation, hot-spot formations, and failure processes. They are also launching an effort to link CHEETAH to hydrodynamic codes so they can create even more complete models of high-explosive detonation. This effort will serve not only DOD explosives formulation work but also help Livermore fulfill its responsibilities to the DOE Stockpile Stewardship Program. In the case of CHEETAH, DOE resources that were leveraged to benefit DOD are in turn being leveraged to benefit DOE missions at Livermore.

Codes to Assess Safety

In addition to CHEETAH, other Livermore codes are proving useful for evaluating explosive performance and effects. For example, CALE is used in Laboratory projects to assess a variety of explosive and nonexplosive problems. Livermore scientists are using it for such applications as simulations to evaluate safety concerns at missile launch sites.

In April 1986, at 8.7 seconds into the launch of an Air Force Titan T34D-9 space vehicle from Vandenberg Air Force Base, one of the vehicle's solid rocket boosters failed. A portion of the booster came loose and fell back down from an altitude of 18,000 feet at a speed of 320 feet per second, hitting the ground sideways. That piece weighed an estimated 130,000 pounds, including 110,000 pounds of solid rocket propellant. At impact, it exploded and burned, releasing between 7 and 30 percent of the propellant energy and causing significant damage at Vandenberg.

This launch was representative of the one out of every 30 launches, on average, that ends in failure. Many of those failures result in explosions when unburned motor segments fall back to the ground. Launch safety officials need to know just how destructive and far-reaching such accidents can be. But until recently, they have had only intuition and sparse data to rely on for making their safety judgments.

The upgrade of the solid rocket motor of Titan IVB, which uses a new propellant and a new motor configuration with much longer and more massive booster segments, prompted the Air Force to initiate a project to better understand fallback accidents. One part of that program is being performed by chemical engineer Jon Maienschein and his colleagues. They have developed a computer model that describes in detail the propellant response to fallback accidents and predicts the extent and effects of their energy releases. Simulations using this model will enable launch safety personnel to assess and provide safeguards against the hazards of these accidents.

The model developed by Livermore scientists is called PERMS (propellant energy response to mechanical stimuli). One part of the model describes how a shock front, generated by the impact of a falling booster rocket, causes ignition and burning of explosive material. Data about shock initiation used in the model were obtained through field tests (conducted by Phillips Laboratory at Edwards Air Force Base) that used large explosive boosters to generate shocks from 30,000 to 40,000 times atmospheric pressures over a long duration (Figure 5). Experimenters shocked a sequence of propellant samples up to 5 feet in diameter. Propellant mass in this test was over 48,000 pounds. From these data, they developed a model for the initiation mechanisms and estimated the diameter of propellant necessary to support steady propagation of a reactive shock wave.

The other component of the model is a description of how the booster segment fragments at impact. Fragmentation creates additional burning surfaces as the propellant deforms. The rate at which explosive burning occurs is related to the size and hence surface area of the fragments. Input data for fragmentation and burning rate models were derived from laboratory experiments. The resulting models were validated using large-scale (thousands of pounds of propellant) tests with either steel impact plates or hollow imploding cylinders to simulate the propellants at pressures less than 15,000 times atmospheric pressure.

These two descriptive components form the PERMS model, which is implemented in the CALE hydrodynamic code. Once the conditions of the booster fallback are specified, the model calculates the propellant reactions, considers fragmentation effects, and tracks the progress of reactions over time. The force of the propellant reaction is translated into the equivalent TNT energy release.

Adding Capabilities to the Code

PERMS provided both significant new information about propellant hazards and remarkably good estimates of the explosive behavior that results from both the nose-on and side-on impacts of booster motors falling from the sky. Now, its developers want to look at historic data of incidents in which motor segments fell in orientations where three-dimensional effects are important. To study those effects, they would use the three-dimensional Lagrangian–Eulerian code called ALE3D, which has its origins in Livermore's DYNA3D code.

ALE3D has recently been improved to better model the response of energetic materials to heat and explosive processes. It is now undergoing testing by Laboratory developers Albert Nichols and Richard Couch. The upgraded ALE3D has additional thermal and chemical capabilities as well as calculational options that allow it to accurately depict events over time scales ranging from microseconds to days. It is designed to simulate a typical fire scenario, for example, by following the transport of heat from the exterior of an explosive device to the explosive itself, followed by the thermal decomposition of the explosive. The decomposition gradually changes the material properties of the explosive and induces motion. Depending on how the explosive is

Figure 5. Data for describing the initiation and burning of explosive material are obtained through large-scale tests performed at Edwards Air Force Base, where propellants were shocked at 30,000 to 40,000 times atmospheric pressure, which caused them to explode. (Photograph courtesy of Dr. Claude Merrill, Phillips Laboratory, Edwards Air Force Base.)

confined, the simulation will then depict a slow, relatively benign response or a fast, catastrophic explosion, as happens in real life.

The code has successfully simulated a U.S. Navy "cookoff" safety test in which a slowly heated high explosive is deformed over a long time span (see *S&TR*, June 1997, p. 11). It has also been used in simulations to investigate the use of electron beams for clearing land mines (Figure 6).

The developers are planning to do more testing, using different material models for the chemical reactions and mixtures associated with the explosive processes. They also look forward to using ALE3D to solve other kinds of problems associated with the forging, casting, and extruding processes of manufacturing.

Continuing the Collaboration

As Lawrence Livermore scientists and engineers fulfill their DOE missions, they often find their work tying well to DOD needs and applications. Thus, providing products and services to DOD is both a natural extension of their scientific and technical work as well as a fruitful leveraging of research funding. Aside from accruing advantages to both agencies and the Laboratory, this leveraging ensures that science and technology at Lawrence Livermore are fully in step with national security and defense requirements, whatever they may be.

—Gloria Wilt

Key Words: ALE3D, CALE, Cheetah, explosives, Department of Defense (DOD), fiber-composite sabot, fuse, GLO (global local optimizer), Memorandum of Understanding (MOU), Penetration Augmented Munition (PAM), PERMS (propellant energy response to mechanical stimuli), safety assessment, warhead.

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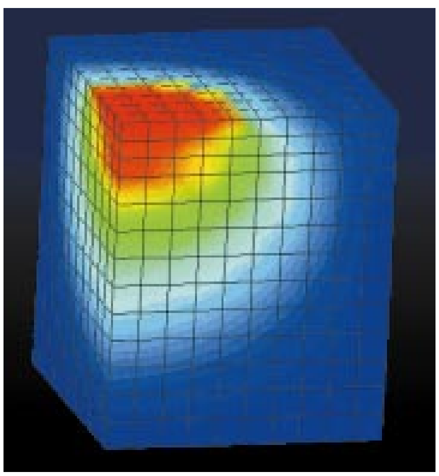

Figure 6. Recently, a representative of the U.S. Navy used Livermore's ALE3D code to investigate the use of electron beams to clear land mines. The thermal-only model shown here is a snapshot in time of a circular region of a land mine being radiatively heated by an electron beam.

About the Scientist

CORY COLL received his A.B. in physics from Johns Hopkins University and his Ph.D. in physics from the University of Pennsylvania. After working at Sandia National Laboratories, California (1974 to 1981), he joined Lawrence Livermore's weapons program as a design physicist and participated in three underground tests at the Nevada Test Site. His career at Livermore was interrupted between 1984 and 1986 when he became, first, staff to the Deputy Undersecretary of Defense for Strategic and Nuclear Forces and, later, a program manager at the Defense Advanced Research Projects Agency (DARPA).

Coll returned to Livermore in 1988 as deputy program manager for Advanced Applications in the Laser Programs Directorate and moved to the Laboratory Director's Office in 1992. Currently, he is staff to the director of the Department of Defense Programs Office at the Laboratory.